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Measurement of the branching fraction for $\psi(3770) \rightarrow \gamma \chi_{c0}$ 

BESIII Collaboration

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ABSTRACT

By analyzing a data set of 2.92 fb^{-1} of e^+e^- collision data taken at $\sqrt{s} = 3.773 \text{ GeV}$ and 106.41×10^6 $\psi(3686)$ decays taken at $\sqrt{s} = 3.686 \text{ GeV}$ with the BESIII detector at the BEPCII collider, we measure the branching fraction and the partial decay width for $\psi(3770) \rightarrow \gamma \chi_{c0}$ to be $\mathcal{B}(\psi(3770) \rightarrow \gamma \chi_{c0}) = (6.88 \pm 0.28 \pm 0.67) \times 10^{-3}$ and $\Gamma[\psi(3770) \rightarrow \gamma \chi_{c0}] = (187 \pm 8 \pm 19) \text{ keV}$, respectively. These are the most precise measurements to date.

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1. Introduction

Transitions between charmonium states can be used to shed light on various aspects of Quantum Chromodynamics (QCD), the theory of the strong interactions, in both the perturbative and non-perturbative regimes [1]. The $\psi(3770)$ resonance is the lowest-mass charmonium state lying above the production threshold of open-charm $D\bar{D}$ pairs. It is assumed to be the 1^3D_1 $c\bar{c}$ state with a small 2^3S_1 admixture. Based on this S - D mixing model, predictions have been made [2–6] for the partial widths of the $\psi(3770)$ electric-dipole ($E1$) radiative transitions. These predictions vary over a large range depending on the underlying model assumptions. One of the largest variations in predictions is for the partial width of $\psi(3770) \rightarrow \gamma \chi_{c0}$, with predictions ranging from 213 keV to 523 keV. A precise measurement of the partial width of $\psi(3770) \rightarrow \gamma \chi_{c0}$ provides a stringent test of the various theoretical approaches, thereby providing a better understanding of $\psi(3770)$ decays.

In 2006, the CLEO Collaboration reported the first observation of $\psi(3770) \rightarrow \gamma \chi_{c0/1}$ and measured the partial widths [7,8]. A comparison between their results and predictions of traditional theory models [2–5] indicates that relativistic and coupled-channel effects are necessary ingredients to describe the data. A similar conclusion has been drawn in $\psi(3686) \rightarrow \gamma \chi_{cJ}$ decays [9]. The results of CLEO were normalized to the cross section of $\psi(3770) \rightarrow D\bar{D}$ to obtain the total number of $\psi(3770)$ decays, which assumed

the contribution of $\psi(3770) \rightarrow \text{non-}D\bar{D}$ decays is negligible [27]. Recently, the BESIII Collaboration presented an improved measurement of $\psi(3770) \rightarrow \gamma \chi_{c1}$ [10].

In this Letter, we report on an alternative and complementary measurement of the branching fraction and partial width of $\psi(3770) \rightarrow \gamma \chi_{c0}$ using $\chi_{c0} \rightarrow 2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $3(\pi^+\pi^-)$ and K^+K^- decays. The results of our measurements are obtained by taking the relative strength with respect to the well-known $\psi(3686)$ radiative $E1$ transition [11]. In this way, the measurement will not depend on knowledge of the χ_{cJ} branching fractions to light hadron final states, which have large uncertainties [7]. This measurement forms an independent and more precise benchmark that can be compared to the predictions of various theoretical models.

2. BESIII detector and Monte Carlo simulation

In this work, we use 2.92 fb^{-1} of e^+e^- collision data taken at $\sqrt{s} = 3.773 \text{ GeV}$ [12], and 106.41×10^6 $\psi(3686)$ decays taken at $\sqrt{s} = 3.686 \text{ GeV}$ [13] with the BESIII detector. These are labeled the $\psi(3770)$ and $\psi(3686)$ data samples, respectively, throughout this Letter.

The BESIII detector [14] has a geometrical acceptance of 93% of 4π and consists of four main components. In the following, we describe each detector component starting from the innermost (closest to the interaction region) to the most outside layer. The inner three components are immersed in the 1 T magnetic field of a superconducting solenoid. First, a small-cell, helium-based main drift chamber (MDC) with 43 layers provides charged particle tracking and measurement of ionization energy loss (dE/dx). The average single wire resolution is 135 μm , and the momentum resolution for 1 GeV electrons in a 1 T magnetic field is 0.5%. The next detector after the MDC is a time-of-flight system (TOF) used for particle identification. It is composed of a barrel part made of two layers of 88 plastic scintillators, each with 5 cm thickness and 2.4 m length; and two endcaps, each with 96 fan-shaped plastic scintillators of 5 cm thickness. The time resolution is 80 ps in the barrel, and 110 ps in the endcaps, corresponding to a K/π separation better than 2σ for momenta up to about 1.0 GeV. The third detec-

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tor component is an electromagnetic calorimeter (EMC) made of 6240 CsI(Tl) crystals arranged in a cylindrical shape (barrel) plus two endcaps. For 1.0 GeV photons, the energy resolution is 2.5% in the barrel and 5% in the endcaps, and the position resolution is 6 mm in the barrel and 9 mm in the endcaps. Outside the EMC, a muon chamber system (MUC) is incorporated in the return iron of the superconducting magnet. It is made of 1272 m² of resistive plate chambers arranged in 9 layers in the barrel and 8 layers in the endcaps. The position resolution is about 2 cm.

A GEANT4 [15] based Monte Carlo (MC) simulation software package, which includes the geometric description of the detector and the detector response, is used to determine the detection efficiency of the signal process and to estimate the potential peaking backgrounds. Signal MC samples of $\psi(3686)/\psi(3770) \rightarrow \gamma\chi_{cJ}$ are generated with the angular distribution that corresponds to an $E1$ transition, and the χ_{cJ} decays to light hadron final states are generated according to a phase-space model. Particle decays are modeled using EvtGen [16], while the initial production is handled by the MC generator KKMC [17], in which both initial state radiation (ISR) effects [18] and final state radiation (FSR) effects [19] are considered. For the background studies of $\psi(3686)$ decays, 106×10^6 MC events of generic decays $\psi(3686) \rightarrow \text{anything}$ are produced at $\sqrt{s} = 3.686$ GeV. For the background studies of $\psi(3770)$ decays, MC samples of $\psi(3770) \rightarrow D^0\bar{D}^0$, $\psi(3770) \rightarrow D^+D^-$, $\psi(3770) \rightarrow \text{non-}D\bar{D}$ decays, ISR production of $\psi(3686)$ and J/ψ , QED, and $q\bar{q}$ continuum processes are produced at $\sqrt{s} = 3.773$ GeV. The known decay modes of the J/ψ , $\psi(3686)$ and $\psi(3770)$ are generated with branching fractions taken from the PDG [11], and the remaining events are generated with Lundcharm [20].

3. Analysis

To select candidate events for $\psi(3686)/\psi(3770) \rightarrow \gamma\chi_{cJ}$ with $\chi_{cJ} \rightarrow 2(\pi^+\pi^-)/K^+K^-\pi^+\pi^-/3(\pi^+\pi^-)/K^+K^-$, we require at least 4/4/6/2 charged tracks to be reconstructed in the MDC, respectively. All charged tracks used in this analysis are required to be within a polar-angle (θ) range of $|\cos\theta| < 0.93$. It is required that all charged tracks originate from the interaction region defined by $|V_z| < 10$ cm and $|V_{xy}| < 1$ cm, where $|V_z|$ and $|V_{xy}|$ are the distances of closest approach of the charged track to the collision point in the beam direction and in the plane perpendicular to the beam, respectively.

Charged particles are identified by confidence levels for kaon and pion hypotheses calculated using dE/dx and TOF measurements. To effectively separate pions and kaons, a track is identified as a pion (or kaon) only if the confidence level for the pion (or kaon) hypothesis is larger than the confidence level for the kaon (or pion) hypothesis.

Photons are selected by exploiting the information from the EMC. It is required that the shower time be within 700 ns of the event start time and the shower energy be greater than 25 (50) MeV in the barrel (endcap) region defined by $|\cos\theta| < 0.80$ ($0.86 < |\cos\theta| < 0.92$). Here, θ is the photon polar angle with respect to the beam direction.

In the selection of $\gamma 2(\pi^+\pi^-)$, background events from radiative Bhabha events in which at least two radiative photons are produced and one of them converts into an e^+e^- pair are suppressed by requiring the opening angle of any $\pi^+\pi^-$ combination be larger than 10° . For the selection of γK^+K^- , the background events of $e^+e^- \rightarrow \gamma e^+e^-$ are suppressed by requiring $E_{\text{EMC}} < 1$ GeV and $E_{\text{EMC}}/p_{\text{MDC}} < 0.8$ for each charged kaon, where E_{EMC} and p_{MDC} are the energy deposited in the EMC and the momentum measured by the MDC, respectively.

In each event, there may be several different charged and/or neutral track combinations which satisfy the selection criteria for

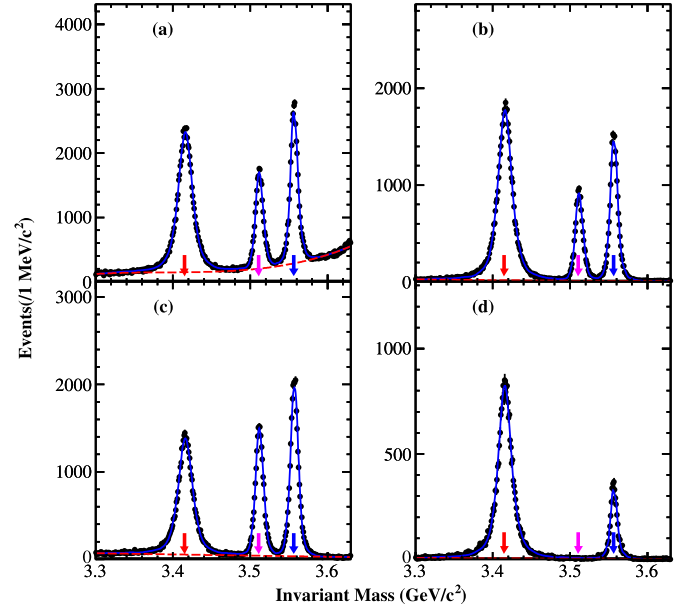


Fig. 1. Invariant mass spectra of the (a) $2(\pi^+\pi^-)$, (b) $K^+K^-\pi^+\pi^-$, (c) $3(\pi^+\pi^-)$ and (d) K^+K^- combinations for the $\psi(3686)$ data. The dots with error bars are for data and the blue solid lines are the fit results. The red dashed lines are the fitted backgrounds. The red, pink and blue arrows show the χ_{c0} , χ_{c1} and χ_{c2} nominal masses, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

each light hadron final state. Each combination is subjected to a 4C kinematic fit for the hypotheses of $\psi(3686)/\psi(3770) \rightarrow \gamma 2(\pi^+\pi^-)$, $\gamma K^+K^-\pi^+\pi^-$, $\gamma 3(\pi^+\pi^-)$ and γK^+K^- . For each final state, if more than one combination satisfies the selection criteria, only the combination with the least χ^2_{4C} is retained, where χ^2_{4C} is the chi-square of the 4C kinematic fit. The final states with $\chi^2_{4C} < 25$ are kept for further analysis.

To identify the χ_{cJ} decays, we examine the invariant mass spectra of the light hadron final states. Fig. 1 shows the corresponding mass spectra for the $\psi(3686)$ data, in which clear χ_{c0} , χ_{c1} and χ_{c2} signals are observed. Since the χ_{c1} cannot decay into two pseudoscalar mesons because of spin-parity conservation, the χ_{c1} signal cannot be observed in the K^+K^- invariant mass spectrum. By fitting these spectra separately, we obtain the numbers of χ_{cJ} observed from the $\psi(3686)$ data, $N_{\psi(3686)}$, which are summarized in Table 1. In the fits, the χ_{cJ} signals are described by the MC simulated line-shapes convoluted by Gaussian functions for the resolution. Backgrounds in the four channels are described by 3/3/3/1-parameter polynomial functions. The parameters of the convoluted Gaussian functions and the Chebychev polynomial functions are all free.

Fig. 2 shows the corresponding mass spectra for the $\psi(3770)$ data, in which clear peaks can be observed for the χ_{c0} decays. Fitting to these spectra similarly, we obtain the number of χ_{cJ} ($J = 0, 1$) decays observed from the $\psi(3770)$ data, $N_{\psi(3770)}$, which are summarized in Table 1. Due to the limited statistics, the decay $\psi(3770) \rightarrow \gamma\chi_{c2}$ is not further considered in this analysis. The means and widths of the convoluted Gaussian functions for the χ_{c0} signals are left free. For the χ_{c1} , the mean and width of the convoluted Gaussian functions are fixed at the values taken from the fits to the $\psi(3686)$ data. Backgrounds in the four channels are described by 6/2/6/2-parameter polynomial functions.

The background events from $e^+e^- \rightarrow (\gamma_{\text{ISR}})\psi(3686)$ produced near $\sqrt{s} = 3.773$ GeV have the same event topologies as those from $\psi(3770)$ decays and are indistinguishable from $\psi(3770)$ decays. In the fits to the $\psi(3770)$ data, the size and line-shape of

Table 1

Measured R_{cj} (%), where $N_{\psi(3770)}$ and $N_{\psi(3686)}$ are the (peaking background corrected) numbers of χ_{cj} observed from the $\psi(3770)$ and $\psi(3686)$ data, $\epsilon_{\psi(3770)}$ and $\epsilon_{\psi(3686)}$ are the detection efficiencies (%). The uncertainties are statistical only.

| $\chi_{cj} \rightarrow LH$ | | $J = 0$ | $J = 1$ |
|----------------------------|-------------------------|-----------------|-----------------|
| $2(\pi^+\pi^-)$ | $N_{\psi(3770)}$ | 756 ± 51 | 80 ± 26 |
| | $\epsilon_{\psi(3770)}$ | 24.1 ± 0.2 | 25.7 ± 0.2 |
| | $N_{\psi(3686)}$ | 59976 ± 318 | 19712 ± 175 |
| | $\epsilon_{\psi(3686)}$ | 24.9 ± 0.2 | 26.5 ± 0.2 |
| | R_{cj} | 6.64 ± 0.45 | 2.13 ± 0.69 |
| $K^+K^-\pi^+\pi^-$ | $N_{\psi(3770)}$ | 716 ± 54 | 46 ± 24 |
| | $\epsilon_{\psi(3770)}$ | 24.0 ± 0.2 | 25.4 ± 0.2 |
| | $N_{\psi(3686)}$ | 46929 ± 240 | 11576 ± 115 |
| | $\epsilon_{\psi(3686)}$ | 23.3 ± 0.2 | 24.9 ± 0.2 |
| | R_{cj} | 7.56 ± 0.57 | 2.00 ± 1.04 |
| $3(\pi^+\pi^-)$ | $N_{\psi(3770)}$ | 502 ± 54 | 76 ± 27 |
| | $\epsilon_{\psi(3770)}$ | 18.5 ± 0.2 | 20.0 ± 0.2 |
| | $N_{\psi(3686)}$ | 36536 ± 237 | 19593 ± 153 |
| | $\epsilon_{\psi(3686)}$ | 18.1 ± 0.2 | 19.6 ± 0.2 |
| | R_{cj} | 6.86 ± 0.74 | 1.94 ± 0.69 |
| K^+K^- | $N_{\psi(3770)}$ | 283 ± 24 | – |
| | $\epsilon_{\psi(3770)}$ | 32.5 ± 0.2 | – |
| | $N_{\psi(3686)}$ | 21452 ± 154 | – |
| | $\epsilon_{\psi(3686)}$ | 32.1 ± 0.2 | – |
| | R_{cj} | 6.65 ± 0.57 | – |
| Averaged R_{cj} | | 6.89 ± 0.28 | 2.03 ± 0.44 |

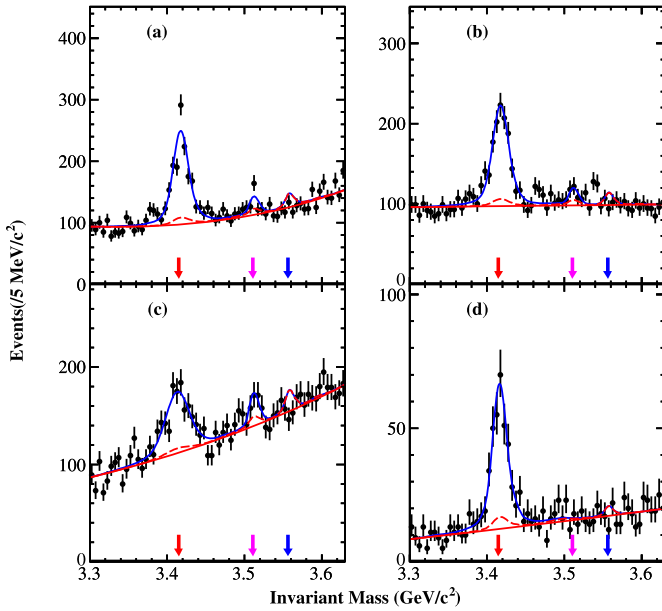


Fig. 2. Invariant mass spectra of the (a) $2(\pi^+\pi^-)$, (b) $K^+K^-\pi^+\pi^-$, (c) $3(\pi^+\pi^-)$ and (d) K^+K^- combinations for the $\psi(3770)$ data. The dots with error bars are data and the blue solid lines are the fit results. The red solid lines are the fitted combinatorial backgrounds. The red dashed lines are the sums of the peaking and fitted combinatorial backgrounds. The red, pink and blue arrows show the χ_{c0} , χ_{c1} and χ_{c2} nominal masses, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

such backgrounds are fixed according to MC simulations, with the numbers of background events being determined by

$$N_{\chi_{cj}}^b = \sigma_{\psi(3686)}^{\chi_{cj}, LH, obs} \cdot \mathcal{L}_{\psi(3770)} \cdot \eta, \quad (1)$$

where $\mathcal{L}_{\psi(3770)}$ is the integrated luminosity of the $\psi(3770)$ data, $\sigma_{\psi(3686)}^{\chi_{cj}, LH, obs}$ is the observed cross section of $e^+e^- \rightarrow \psi(3686) \rightarrow \gamma\chi_{cj}$ with $\chi_{cj} \rightarrow LH$, in which LH denotes $2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $3(\pi^+\pi^-)$ and K^+K^- . In this work, we assume that

there is no other effect affecting the $\psi(3686)$ and $\psi(3770)$ production in the energy range from 3.73 to 3.89 GeV. The variable η represents the rate of misidentifying $\psi(3686)$ decays as $\psi(3770)$ decays, which is obtained by analyzing 1.5×10^6 MC events of $\psi(3686) \rightarrow \gamma\chi_{cj}$ with $\chi_{cj} \rightarrow LH$ generated at $\sqrt{s} = 3.773$ GeV. The observed cross section for $\psi(3686) \rightarrow \gamma\chi_{cj}$ with $\chi_{cj} \rightarrow LH$ at a center-of-mass energy of \sqrt{s} is given by

$$\sigma_{\psi(3686)}^{\chi_{cj}, LH, obs} = \int \sigma_{\psi(3686)}^{\chi_{cj}, LH}(s') f(s') F(x, s) G(s, s') ds' dx, \quad (2)$$

where $s' \equiv s(1-x)$ is the square of the actual center-of-mass energy of the e^+e^- after radiating photon(s), x is the fraction of the radiative energy to the beam energy; $f(s')$ is the phase space factor, $(E_\gamma(s')/E_\gamma^0)^3$, in which $E_\gamma(s')$ and E_γ^0 are the photon energies in $\psi(3686) \rightarrow \gamma\chi_{cj}$ transition at $\sqrt{s'}$ and at the $\psi(3686)$ mass, respectively; $F(x, s)$ is the sampling function describing the radiative photon energy fraction x at \sqrt{s} [18]; $G(s, s')$ is a Gaussian function describing the distribution of the collision energy with an energy spread $\sigma_E = 1.37$ MeV as achieved at BEPCII; $\sigma_{\psi(3686)}^{\chi_{cj}, LH}(s')$ is the cross section described by the Breit–Wigner function

$$\sigma_{\psi(3686)}^{\chi_{cj}, LH}(s') = \frac{12\pi \Gamma_{\psi(3686)}^{ee} \Gamma_{\psi(3686)}^{\text{tot}} \mathcal{B}_{\psi(3686)}^{\chi_{cj}, LH}}{(s'^2 - M_{\psi(3686)}^2)^2 + (\Gamma_{\psi(3686)}^{\text{tot}} M_{\psi(3686)})^2}, \quad (3)$$

in which $\Gamma_{\psi(3686)}^{ee}$ and $\Gamma_{\psi(3686)}^{\text{tot}}$ are, respectively, the leptonic width and total width of the $\psi(3686)$, $M_{\psi(3686)}$ is the $\psi(3686)$ mass, $\mathcal{B}_{\psi(3686)}^{\chi_{cj}, LH}$ is the combined branching fraction of $\psi(3686) \rightarrow \gamma\chi_{cj}$ with $\chi_{cj} \rightarrow LH$. Here, the upper limit of x is set at $1 - m_{\chi_{cj}}^2/s$, where $m_{\chi_{cj}}$ is the χ_{cj} nominal mass. We determine the branching fraction $\mathcal{B}_{\psi(3686)}^{\chi_{cj}, LH}$ by dividing the number of χ_{cj} decays of $\psi(3686)$ by the total number of $\psi(3686)$ and by the corresponding efficiency obtained in this work. The rates η of misidentifying $\psi(3686) \rightarrow \gamma\chi_{c0/1/2}$ as $\psi(3770) \rightarrow \gamma\chi_{c0/1/2}$ are estimated to be $4.72/6.40/7.60 \times 10^{-4}$, $4.40/6.27/7.57 \times 10^{-4}$, $3.53/4.95/6.14 \times 10^{-4}$ and $6.56/-/11.02 \times 10^{-4}$ for $\chi_{c0/1/2} \rightarrow 2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $3(\pi^+\pi^-)$ and K^+K^- , respectively. These lead to the number of background events from $e^+e^- \rightarrow$

$(\gamma_{\text{ISR}})\psi(3686)$ to be $90.6 \pm 3.4/37.5 \pm 1.4/76.5 \pm 2.9$, $70.0 \pm 2.7/23.5 \pm 0.9/51.0 \pm 1.9$, $56.6 \pm 2.2/39.7 \pm 1.5/73.5 \pm 2.8$ and $34.9 \pm 1.3/-11.1 \pm 0.4$ for $\psi(3770) \rightarrow \gamma \chi_{c0/1/2}$ with $\chi_{c0/1/2} \rightarrow 2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $3(\pi^+\pi^-)$ and K^+K^- decays, respectively. The errors arise from uncertainties in the $\psi(3686)$ resonance parameters, the integrated luminosity of the $\psi(3770)$ data $\mathcal{L}_{\psi(3770)}$ and the misidentification rates η . In Eq. (1), the number of background events depends on the ratio of the misidentification rate η over the efficiency $\epsilon_{\psi(3686)}$ of reconstructing $\psi(3686) \rightarrow \chi_{cj}$. Since η and $\epsilon_{\psi(3686)}$ all contain the simulation of $\chi_{cj} \rightarrow LH$, a possible systematic uncertainty from the simulation of $\chi_{cj} \rightarrow LH$ is canceled here.

4. Results

The ratio of the branching fraction for $\psi(3770) \rightarrow \gamma \chi_{cj}$ divided by the branching fraction for $\psi(3686) \rightarrow \gamma \chi_{cj}$ is determined channel by channel as

$$R_{cj} = \frac{\mathcal{B}[\psi(3770) \rightarrow \gamma \chi_{cj}]}{\mathcal{B}[\psi(3686) \rightarrow \gamma \chi_{cj}]} = \frac{N_{\psi(3770)} \cdot N_{\psi(3686)}^{\text{tot}} \cdot \epsilon_{\psi(3686)}}{N_{\psi(3686)} \cdot N_{\psi(3770)}^{\text{tot}} \cdot \epsilon_{\psi(3770)}}, \quad (4)$$

where $N_{\psi(3686)}$ and $N_{\psi(3770)}$ are the numbers of χ_{cj} observed from the $\psi(3686)$ and $\psi(3770)$ data, $N_{\psi(3686)}^{\text{tot}}$ and $N_{\psi(3770)}^{\text{tot}}$ are the total numbers of $\psi(3686)$ and $\psi(3770)$ decays, $\epsilon_{\psi(3686)}$ and $\epsilon_{\psi(3770)}$ are the efficiencies of reconstructing $\psi(3686)$ and $\psi(3770) \rightarrow \gamma \chi_{cj}$ with $\chi_{cj} \rightarrow LH$ estimated by MC simulations, respectively. Here, $N_{\psi(3770)}^{\text{tot}}$ is determined by $\sigma_{\psi(3770)}^{\text{obs}} \cdot \mathcal{L}_{\psi(3770)}$, where $\sigma_{\psi(3770)}^{\text{obs}} = (7.15 \pm 0.27 \pm 0.27)$ nb is the cross section for $\psi(3770)$ production [21–23] and $\mathcal{L}_{\psi(3770)}$ is the integrated luminosity of the $\psi(3770)$ data set [12].

Table 1 summarizes the ratios R_{cj} measured via the different channels. The results are consistent within statistical uncertainties. From these measurements, we obtain the statistical-weighted averages $\bar{R}_{c0} = (6.89 \pm 0.28 \pm 0.65)\%$ and $\bar{R}_{c1} = (2.03 \pm 0.44 \pm 0.66)\%$, where the first uncertainty is statistical and the second systematic.

In the measurements of $\bar{R}_{c0/1}$, the systematic uncertainty arises from the uncertainties in the total number (0.81%) of $\psi(3686)$ decays ($N_{\psi(3686)}^{\text{tot}}$ [13]); the integrated luminosity (1.0%) of the $\psi(3770)$ data ($\mathcal{L}_{\psi(3770)}$ [12]); the cross section (5.3%) for $\psi(3770)$ ($\sigma_{\psi(3770)}^{\text{obs}}$ [21–23]); the photon selection (1.4%), assigned based on 1.0% per photon [24]; the MDC tracking (2.6%/4.0%); the particle identification (2.6%/4.0%); the statistical uncertainty (1.0%) of the efficiency due to the size of the simulated event sample; the 4C kinematic fit (1.0%), estimated by comparing the measurements with and without the kinematic fit correction; the fit to mass spectra (6.4%/31.5%), estimated by comparing the measurements with alternative fit ranges (± 20 MeV/ c^2), signal shape (simple Breit–Wigner function) and background shapes (± 1 order of the polynomial functions); and the subtraction of $\psi(3686)$ peaking background (0.5%/2.0%). The efficiencies of the MDC tracking and particle identification for K^+ or π^+ are examined by the doubly tagged hadronic $D\bar{D}$ events. The difference between the efficiencies of data and MC is assigned as an uncertainty. Then, their effects on $\bar{R}_{c0/1}$ are estimated to be 2.6%/4.0%. Table 2 summarizes these uncertainties. Adding them in quadrature, we obtain the total systematic uncertainty for $\bar{R}_{c0/1}$ to be 9.4%/32.6%.

Multiplying \bar{R}_{cj} by the branching fraction $\mathcal{B}[\psi(3686) \rightarrow \gamma \chi_{cj}]$ (and the total width $\Gamma_{\psi(3770)}^{\text{tot}}$) taken from the PDG [11], we obtain the branching fractions (and the partial widths) for $\psi(3770) \rightarrow \gamma \chi_{cj}$, which are summarized in Table 3, where the first uncertainty is statistical and the second systematic. In the measurement of $\mathcal{B}[\psi(3770) \rightarrow \gamma \chi_{cj}]$ (and $\Gamma[\psi(3770) \rightarrow \gamma \chi_{cj}]$), the systematic uncertainty arises from the uncertainties of $\bar{R}_{c0/1}$ and the uncer-

Table 2

Systematic uncertainties (%) in the measurements of \bar{R}_{cj} .

| | \bar{R}_{c0} | \bar{R}_{c1} |
|--|----------------|----------------|
| $N_{\psi(3686)}^{\text{tot}}$ [13] | 0.81 | 0.81 |
| $\sigma_{\psi(3770)}^{\text{obs}}$ [21–23] | 5.3 | 5.3 |
| $\mathcal{L}_{\psi(3770)}$ [12] | 1.0 | 1.0 |
| MC statistics | 1.0 | 1.0 |
| Photon selection | 1.4 | 1.4 |
| MDC tracking | 2.6 | 4.0 |
| Particle identification | 2.6 | 4.0 |
| 4C kinematic fit | 1.0 | 1.0 |
| Fit to mass spectra | 6.4 | 31.5 |
| Background subtraction | 0.5 | 2.0 |
| Total | 9.4 | 32.6 |

Table 3

Comparisons of the partial widths for $\psi(3770) \rightarrow \gamma \chi_{cj}$ (in keV), where \mathcal{B} and Γ denote the branching fraction and the partial width for $\psi(3770) \rightarrow \gamma \chi_{cj}$, respectively. For the BESIII results, the first uncertainty is statistical and the second systematic. Detailed explanations about the CLEO results can be found in footnote 1.

| Experiments | $J = 0$ | $J = 1$ |
|---|--------------------------|--------------------------|
| $\mathcal{B}^{\text{BESIII}} (\times 10^{-3})$ | $6.88 \pm 0.28 \pm 0.67$ | $1.94 \pm 0.42 \pm 0.64$ |
| $\mathcal{B}^{\text{BESIII}} (\times 10^{-3})$ [10] | – | $2.48 \pm 0.15 \pm 0.23$ |
| Γ^{BESIII} | $187 \pm 8 \pm 19$ | $53 \pm 12 \pm 18$ |
| Γ^{BESIII} [10] | – | $67.5 \pm 4.1 \pm 6.7$ |
| Γ^{CLEO} [7,8] | 172 ± 30 | 70 ± 17 |
| $\Gamma^{\text{CLEO}}_{\text{corrected}}$ | 192 ± 24 | 72 ± 16 |
| Theories | | |
| Rosner [2] (non-relativistic) | 523 ± 12 | 73 ± 9 |
| Ding–Qing–Chao [3] | | |
| non-relativistic | 312 | 95 |
| relativistic | 199 | 72 |
| Eichten–Lane–Quigg [4] | | |
| non-relativistic | 254 | 183 |
| with coupled channels | 225 | 59 |
| corrections | | |
| Barnes–Godfrey–Swanson [5] | | |
| non-relativistic | 403 | 125 |
| relativistic | 213 | 77 |
| NRCQM [6] | 218 | 70 |

tainties of $\mathcal{B}[\psi(3686) \rightarrow \gamma \chi_{c0/1}]$ of 2.7/3.2% (and the uncertainty of $\Gamma_{\psi(3770)}^{\text{tot}}$ of 3.7%).

5. Summary

In summary, by analyzing 2.92 fb^{-1} of e^+e^- collision data taken at $\sqrt{s} = 3.773 \text{ GeV}$ and 106.41×10^6 $\psi(3686)$ decays taken at $\sqrt{s} = 3.686 \text{ GeV}$ with the BESIII detector at the BEPCII collider, we measure the branching fraction $\mathcal{B}(\psi(3770) \rightarrow \gamma \chi_{c0}) = (6.88 \pm 0.28 \pm 0.67) \times 10^{-3}$ and the partial width $\Gamma[\psi(3770) \rightarrow \gamma \chi_{c0}] = (187 \pm 8 \pm 19) \text{ keV}$. These are obtained by first measuring the ratio with respect to the accurately known branching fraction for $\psi(3686) \rightarrow \gamma \chi_{cj}$ decays. Our results are, thereby, not influenced by the uncertainties in the branching fractions of χ_{cj} decays to light hadrons as done in Ref. [7]. The branching fraction and partial width for $\psi(3770) \rightarrow \gamma \chi_{c1}$ measured in this work are consistent with our previous measurement [10] within errors. Table 3 compares the $\Gamma[\psi(3770) \rightarrow \gamma \chi_{c0/1}]$ measured at BESIII with those measured by CLEO [7,8]¹ and the theoretical calculations from Refs. [2–6]. The partial width $\Gamma[\psi(3770) \rightarrow \gamma \chi_{c0}]$ measured at

¹ The CLEO measurements were based on the total width $\Gamma_{\psi(3770)}^{\text{tot}} = (23.6 \pm 2.7) \text{ MeV}$ [25] and the cross section $\sigma_{\psi(3770) \rightarrow D\bar{D}}^{\text{obs}} = (6.39 \pm 0.10^{+0.17}_{-0.08}) \text{ nb}$ for determining the total number of $\psi(3770)$ decays, where the $\psi(3770) \rightarrow \text{non-}D\bar{D}$ decays were neglected. In addition, CLEO [7] cited $\mathcal{B}(\psi(3686) \rightarrow \gamma \chi_{c0}) = (9.22 \pm$

BESIII is consistent within errors with the one measured by CLEO with an improved precision. These results underline the fact that the traditional models [3–5] with a relativistic assumption or a coupled-channel correction agree quantitatively better with the experimental data than those [2–5] based upon non-relativistic calculations. For these traditional models, the non-relativistic calculations clearly overestimate the partial width $\Gamma[\psi(3770) \rightarrow \gamma \chi_{cJ}]$. The experimental data also support the recent calculation based on the non-relativistic constituent quark model (NRCQM) [6]. Together with further theoretical developments, our results aim to contribute to a deeper understanding of the dynamics of charmonium decays above the open-charm threshold.

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$0.11 \pm 0.46\%$ and $\mathcal{B}(\psi(3686) \rightarrow \gamma \chi_{c1}) = (9.07 \pm 0.11 \pm 0.54)\%$ to determine $\mathcal{B}(\psi(3770) \rightarrow \gamma \chi_{cJ})$ from Ref. [26]. Although CLEO determined the branching fraction of $\psi(3770) \rightarrow \text{non-}D\bar{D}$ decays to be $(-3.3 \pm 1.4_{-6.6}^{+4.8})\%$ and set an upper limit of 9% at 90% confidence level [27], the PDG value for $\Gamma_{\psi(3770)}^{D\bar{D}}/\Gamma_{\psi(3770)}^{\text{tot}}$ [28] from four measurements at BESII [22,29–31] implied the branching fraction for $\psi(3770) \rightarrow \text{non-}D\bar{D}$ decays to be $(14.7 \pm 3.2)\%$. At present, the PDG value for $\Gamma_{\psi(3770)}^{D\bar{D}}/\Gamma_{\psi(3770)}^{\text{tot}}$ gives the branching fraction of $\psi(3770) \rightarrow \text{non-}D\bar{D}$ decays to be $(7_{-9}^{+8})\%$ [11]. Therefore, for better comparisons, we also list the corrected CLEO partial widths with the same input values as those used in our measurements, which are $\sigma_{\psi(3770)}^{\text{obs}} = (7.15 \pm 0.27 \pm 0.27)$ nb [21–23], $\Gamma_{\psi(3770)}^{\text{tot}} = (27.2 \pm 1.0)$ MeV, $\mathcal{B}(\psi(3686) \rightarrow \gamma \chi_{c0}) = (9.99 \pm 0.27)\%$ and $\mathcal{B}(\psi(3686) \rightarrow \gamma \chi_{c1}) = (9.55 \pm 0.31)\%$ [11].